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Analysis of Cable-actuated Parallel Robot with Variable Length and Velocity cable

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Abstract

This paper is concerned with modeling, analysis of cable-actuated robotic manipulators with non-negligible cable mass and velocity. The manipulator architecture is a simplified version adopted from the structure of the Feed cabin to track radio source in 500m aperture spherical radio telescope (FAST), the China design of next generation giant radio telescopes. According to the model, to begin with, the governing dynamic equation of motion of such structure is derived using the principle of virtual work, at the same time the Newton-Euler equation for a varying mass system is employed to the varied length cable. Next, the numerical examples of the system are given. It is showed that the limb with variable length and velocity cable does contribute to the dynamical forces required to a typical trajectory.

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Cable-actuated robotic; dynamics analysis; varying mass system

1. Introduction

Cable-actuated parallel robots (CPR) employ cables to control the end-effector posture, instead of rigid-linked actuators. Such structure possesses some valuable characteristics: simple in form, large workspace, low inertia, high payload to weight ratio, transportability, reconfigurability, and fully remote actuation [1]. Research has been performed based on practical implementation, and a large number of Cable-actuated robots have been developed such as the RoboCrane for moving heavy loads over large workspace[2] , the WARP manipulator for assembling of lightweight objects [3], and the SkyCam[4] for a stabilized camera system. When cables are utilized to replace rigid links to the feed cabin to track radio source in 500-m aperture spherical radio telescope (FAST)， we get Cable-actuated parallel robot (CPR)-the large FAST system for a radio telescope receiver[5][6] .

CPR can be divided into three classes. The fully constrained robots are the first class, in which by controlling the cables length their position and orientation is determined and fixed. For a cable suspended

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robot to be fully constrained it must have at least seven cables [10] The second type of CPR are point mass, where all the cables intersect at a single point while the robot is suspended underneath this point [4][11].Third, are the under constrained CPR in which the cables do not fully constrain the robot's configuration, and under the effect of external force they can move. Usually the external force is gravity, and the robot tends to reach the equilibrium where its potential energy is minimal. The number of cables for under constrained CPR is six or less [5][7]. The large FAST system is an under-constrained CPR consisting of six cables.

There are a lot of prior studies on kinematics and workspace analysis [12], force-closure analysis [13][14], optimal cable tension distribution[15], and dynamics and control [5][8][9][16]. In this paper, we present a CPR inverse dynamical model considering the affects of cable length varying and moving velocity to the tension in cable. First, based on the principle of virtual work and Newton – Euler equations for a varying mass system, the inverse dynamic formulation of CPR is established. Then, numerical simulations illustrate the cable tension of four cases: with and without considering the varying cable length system, cable moving in two different velocities.

2. Architecture

The architecture of the cable-actuated parallel robot considered for our studies is shown in Fig. 1. Ai denotes the fixed base points of the limbs, bi denotes the connection points of the limbs on the moving platform, di denotes the limb lengths. There is a pulley in Ai for cable pass. This architecture consists of 6 UPR parallel structures. The moving platform is supported by six limbs of identical kinematic structure. Each limb connects the fixed base to the moving platform by a universal joint (U) followed by a prismatic joint (P) and another spherical joint (S). The kinematic structure of a prismatic joint is used to model the elongation of each cable-actuated limb.

For the purpose of analysis, a coordinate frame $O(x,y,z)$ is attached to the fixed base and another coordinate frame $B(u,v,w)$ is attached to the moving platform. Furthermore, a local coordinate frame $C(x_i, y_i, z_i)$ is attached to each limb such that its origin is located at point A_i, the Z_i axis points inverse from A_i to b_i, the Y_i axis is parallel to the cross product of two unit vectors defined along the Z_i and Z axes, and the X_i axis is defined by the right-hand rule. For convenience, the origin of frame B is located at the mass center P of the moving platform. The location of the moving platform can be described by a position vector, ***Op***, and a rotation matrix, ${}^{A}R_{B}$.

Let the rotation matrix be defined by the roll, pitch, and yaw angles, namely, a rotation of Φx about the fixed x-axis, followed by a rotation of Φy about the fixed y-axis, and a rotation of Φz about the fixed z-axis.

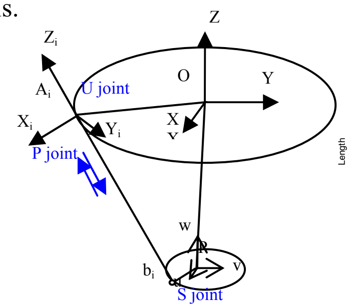

Fig. 1. The sketch of a cable- robot

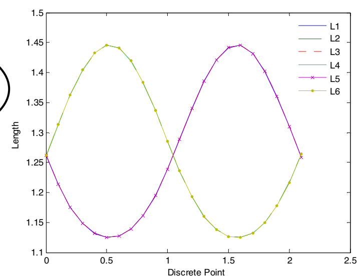

Fig. 2 Cable Length vs. Discrete Point

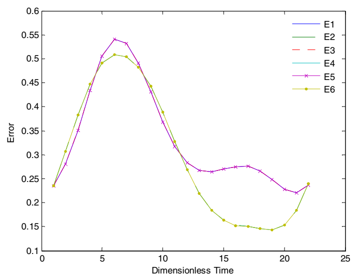

Fig. 3 Error of the first two models

The position and orientation of the center of the moving platform is denoted by $[x, y, z, \Phi_x, \Phi_y, \Phi_z]^T$.

The angular velocity and angular acceleration of the moving platform is given by $\omega_p = \left[\dot{\phi}_x, \dot{\phi}_y, \dot{\phi}_z\right]^T$ and $\dot{\omega}_p = \left[\ddot{\phi}_x, \ddot{\phi}_y, \ddot{\phi}_z\right]^T$

3. **Dynamics**

For the inverse dynamics problem, a desired trajectory of the moving platform is given and the problem is to determine the cable tension required to produce that motion. Here, the dynamical equations of motion are formulated by the principle of virtual work.

The resultant of applied and inertia forces exerted at the center of mass of the moving platform is

$$F_P = \begin{bmatrix} \mathbf{f}_p \\ \mathbf{n}_p \end{bmatrix} = \begin{bmatrix} f_e + m_p\mathbf{g} - m_p\dot{\mathbf{v}}_p \\ n_e - {}^{A}I_p\dot{\boldsymbol{\omega}}_p - \boldsymbol{\omega}_p \times \left({}^{A}I_p\boldsymbol{\omega}_p\right) \end{bmatrix} \tag{1}$$

where $\mathbf{f}_e$ and $\mathbf{n}_e$ are the external force and moment exerted at the center of mass of the moving platform, and ${}^{A}I_p$ the inertia matrix of the moving platform taken about the center of mass and expressed in the fixed frame *O*.

Since in the CPR manipulator is cable driven, it is assumed that due to the elongation in the cable length, the mass of the limbs varies. It is also assumed that the cables are homogeneous, with a circular cross section, and have a density per unit length of ρ_m, The cables are considered to be in a straight line and modeled as rigid bodies, with varying mass of $m_i=\rho_m l_i$ depending on the cable length. The moment of inertia of the cables also vary and can be calculated assuming that they are slender bars with varying length [17]. The moment of inertia of the cables about the fixed point *Ai* is given by:

$${}^{i}I_i = \frac{1}{3}Ml_i^2 = \frac{\rho_m}{3}l_i^3 \tag{2}$$

The time derivative of the mass and moment of inertia of each limb is $\dot{m}_i = \rho_m\dot{l}_i$, ${}^{i}\dot{I}_i = \rho_m l_i^2\dot{l}_i$.

The Newton－Euler equations for a varying mass system can be written as:

$$\sum\mathbf{F}_{ext} = \frac{d}{dt}\left(m_i\,{}^{i}\mathbf{v}_i\right) = m_i\,{}^{i}\dot{\mathbf{v}}_i + \dot{m}_i\,{}^{i}\mathbf{v}_i\ ,\ \sum\mathbf{M}_i = \frac{d}{dt}\left({}^{i}I_i\,{}^{i}\boldsymbol{\omega}_i\right) = {}^{i}I_i\,{}^{i}\dot{\boldsymbol{\omega}}_i + {}^{i}\dot{I}_i\,{}^{i}\boldsymbol{\omega}_i \tag{3}$$

Using the velocity and acceleration of the center of mass of the limbs, by some manipulation we reach the equations of motion of the limbs:

$${}^{i}F_i = \begin{bmatrix} \mathbf{f}_i \\ \mathbf{n}_i \end{bmatrix} = \begin{bmatrix} m_i\,{}^{i}R_A\mathbf{g} - m_i\,{}^{i}\dot{\mathbf{v}}_i - \dot{m}_i\,{}^{i}\mathbf{v}_i \\ -{}^{i}I_i\,{}^{i}\dot{\boldsymbol{\omega}}_i - {}^{i}\boldsymbol{\omega}_i \times \left({}^{i}I_i\,{}^{i}\boldsymbol{\omega}_i\right) - {}^{i}\dot{I}_i\,{}^{i}\boldsymbol{\omega}_i \end{bmatrix} \tag{4}$$

Due to symmetry and the chosen coordinate system, the inertia matrices of the moving platform and the six limbs are all diagonal.

The principle of virtual work can be stated as

$$\delta q^T\tau + \delta\mathbf{x}_p^T F_p + \sum_1^6 \delta^i\mathbf{x}_i^{Ti}F_i = 0 \tag{5}$$

The virtual displacements in Eq.(5), can be expressed in the CPR platform: $\delta q^T = J_p\delta\mathbf{x}_p$ $\delta^i\mathbf{x}_i = {}^{i}J_i\delta\mathbf{x}_p$. Substituting Eq.(4), into (5) yields

$$\delta\mathbf{x}_p^T\left[J_p^T\tau + F_p + \sum_1^6 {}^{i}J_i^{Ti}F_i\right] = 0 \tag{6}$$

Since Eq.(6) is valid for any $\delta\mathbf{x}_p$, it follows that

$$J_p^T\tau + F_p + \sum_1^6 {}^{i}J_i^{Ti}F_i = 0 \tag{7}$$

Hence, if J_p is not singular, input forces can be determined by the inverse transformation of Eq.(7) .

$$\tau = J_p^{-T}\left(-F_p - \sum_1^6 {}^iJ_i^{\,i}F_i\right) \qquad (8)$$

4. Simulation

Based on the deduction, a computer program is developed by using the MATLAB software. The following simulations are performed to reveal the relationship among the cable tension, varied cable mass and velocity. In the program, it is assumed that gravitational force is the only external force acting on the links, and $f_e = 0, n_e = 0$ The system parameters used for the simulations are taken from Wang and Tsai[18][19].

In the simulation, the trajectory of the moving platform is given by: $\Phi_x = \Phi_y = 0$ $\Phi_z = 0.35\sin(\omega t)$,and $p=[-1.5,0,1]m$, where $\omega\sqrt{}3.0$ rad/s and $0 \leqslant \omega t \leqslant 2\pi$.

Four simulations are put forward. The first simulation has fixed cable mass, the second has varied cable length causing the varied cable mass. The cable length varied in Fig.2, and the error of the cable tension between fixed and varied cable mass is plotted in Fig.3. For the third simulation, $\omega=1.5$, the result is plotted in Fig.4. For the forth simulation, $\omega=6$, the result is plotted in Fig.5.Then, the error between Fig.5 and Fig.4 is given in Fig.6.

According to these results, cable tensions increased as cable mass increased, and cable tensions were dependent on velocities. Indeed, it can be noticed that the maximal difference between the tensions in the first two models is about 6% more of the model with fixed cable mass. The maximal cable tension rose when velocity rose, while the minimal cable tension fell when the velocity rose. The maximal error between the tensions in the last two models is about 13% of the third model ($\omega=1.5$).Using this model turns out to be essential to an appropriate design such kind of robot, i.e. to the choice of the motors able to supply enough torques, to the dimensioning of the structure to prevent from plastic deformations, or worse, breakdown.

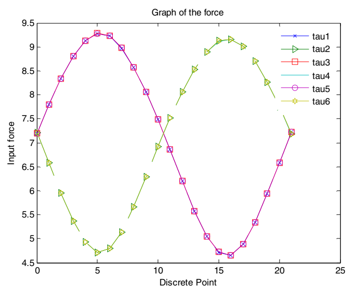

Fig. 4 Input forces ($\omega=1.5$)

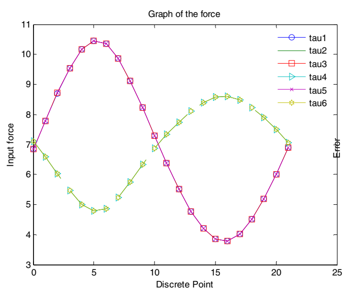

Fig. 5 Input forces ($\omega=6$)

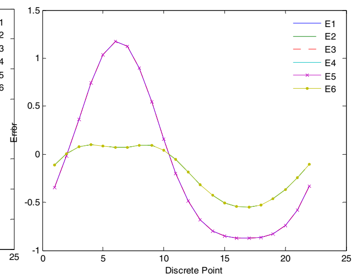

Fig. 6 Error between Fig.5 and Fig.4

5. Conclusion

In this paper, we have presented some results about the effects of cable tension related to the varying cable lengths and velocity on a 6 cables spatial parallel cable-actuated robot. Four models were put forward to study the relationships among the cable tension, cable mass and cable velocity. The simulation results of the models showed that varying cable length and velocity can indeed have an effect on the cable tension. This suggests that large working volume cable manipulators need to be taken into account the effect of cable mass and cable length. At the design level, when we choose the cable depending on the cable tension, the working condition (varied velocity) should be taken into account. Furthermore, this research can potentially be extended to address other important issues, such as adjusting workspace calculations to account for varying cable length and the stiffness of a cable-actuated manipulator.

Acknowledgements

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